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A Model for Vehicle Routing Problem under Returns and Emission Consideration in B2C E-Commerce Logistics

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ABSTRACT

Purpose: With the widespread use of the Internet, electronic commerce allows customers to purchase products from the virtual stores of businesses instead of physical stores. This study addressed a mixed-integer linear programming model for a vehicle routing problem under returns and emission considerations in B2C e-commerce logistics.

***Methodology*:** This study proposes a mathematical model to solve a variant of the vehicle routing problem. The objective is to minimize the fuel consumption cost, penalty cost for unmet demand of returned items, and fixed cost for operating a vehicle. A clustering-based solution algorithm has been introduced to solve large-sized instances within reasonable solution times.

Findings: The numerical analysis for the base case shows that the suggested model can assist decision-makers in coordinating forward distribution and reverse collection decisions within the context of sustainable e-commerce logistics. The result of the adjusted model for minimizing emission shows that a reduction of nearly 17% in total emission amount can be achieved, however, the adjusted model postpones all demand for the collection of returned items. Furthermore, the cluster-based solution approach causes a considerable decrease in solution time while providing promising solutions.

Originality: This study represents a contribution to the existing literature on the subject by considering: i) emission to determine effects on the vehicle routing problem, ii) the postponement of the collection of returned items due to the limited delivery time, iii) proposing the clustering-based solution approach to tackle with larger-sized problems.

***Keywords*:** E-Commerce Logistics, Vehicle Routing Problem, Product Returns, Emission.
***JEL Codes*:** L91.

B2C E-Ticaret Lojistiğinde Geri Dönmüş Ürün ve Emisyonun Dikkate Alındığı Araç Rotalama Problemine İlişkin Bir Model

ÖZET

Amaç: Elektronik ticaret internet kullanımının yaygınlaşması ile birlikte müşterilerin ürünleri fiziksel mağazalar yerine işletmelerin sanal mağazalarından satın almasına olanak sağlamaktadır. Bu çalışmanın amacı, B2C e-ticaret lojistiğinde iade ve emisyon hususları altında bir araç rotalama problemi için bir karma tamsayılı doğrusal programlama modeli önermektir.

Yöntem: Bu çalışma, araç rotalama probleminin bir varyantını çözmek için bir matematiksel model önermektedir. Modelin amacı, yakıt tüketim maliyetini, iade edilen ürünlerin karşılanmayan talebi için ceza maliyetini ve bir aracın işletilmesi için sabit maliyeti en aza indirmektir. Büyük boyutlu örnekleri makul çözüm süreleri içinde çözmek için kümeleme tabanlı bir çözüm algoritması önerilmektedir.

Bulgular: Örnek olay analizi için yapılan sayısal analiz, önerilen modelin sürdürülebilir e-ticaret lojistiği bağlamında ileri yönlü dağıtım ve iade toplama kararlarının koordine edilmesinde karar vericilere yardımcı olabileceğini göstermektedir. Emisyonu en aza indirmeye yönelik düzenlenmiş modelin sonucu, toplam emisyon miktarında yaklaşık %17'lik bir azalma sağlanabileceğini göstermektedir, ancak düzenlenmiş model iade edilen ürünlerin toplanması için olan tüm talebi ertelemektedir. Ayrıca, küme tabanlı çözüm yaklaşımı umut verici çözümler sunarken çözüm süresinde önemli bir azalmaya neden olmaktadır.

Özgünlük: Bu çalışma, i) emisyonun araç rotalama problemi üzerindeki etkileri belirlenmesini, ii) sınırlı teslimat süresi nedeniyle iade edilen ürünlerin toplanmasının ertelenmesini, iii) daha büyük boyutlu problemlerle başa çıkmak için kümeleme tabanlı çözüm yaklaşımını önererek konuyla ilgili mevcut literatüre bir katkı sunmaktadır.

Anahtar kelimeler: E-Ticaret Lojistiği, Araç Rotalama Problemi, Geri Dönmüş Ürün, Emisyon.
JEL kodları: L91.

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1. INTRODUCTION

The e-commerce industry has experienced substantial growth alongside advancements in technology. European business-to-customer (B2C) e-commerce turnover increased to €958 billion in 2024 with 8% growth compared to the previous year (EuroCommerce, 2024: 7). A similar trend can also be observed in emerging markets such as India and China (Tiwari and Sharma, 2023; Li et al., 2021). As an emerging market, the transaction volume of e-commerce has increased to $77,89 billion in 2023 and is anticipated to be $82,39 billion at the end of 2024 in Türkiye (T.C. Ticaret Bakanlığı, 2023: 18). Along with advances in technology, unexpected outbreaks may also affect customer interest in e-commerce. For instance, the COVID-19 outbreak causes considerable changes in both the lifestyle and consumption habits of consumers (Kawasaki et al., 2022; Güngördü Belbağ, 2022). During the COVID-19 era, the increasing trend of e-commerce continues while other industries cope with the recession in the economy.

Globalization, increasing costs, and increasing competitiveness in national and international trade lead logistics companies to provide efficient and productive processes (Samut, 2023; Şahinaslan et al., 2023). The rapid surge in e-commerce sales has exerted considerable pressure on companies to fulfill orders, promptly. Consumers expect expedited and reliable delivery in e-commerce logistics services (Güngördü Belbağ, 2022). The distribution of products becomes a prominent process to meet or exceed customer expectations. Determining vehicle routes is getting more time-consuming and costly process in the e-commerce industry, especially for last-mile delivery operations. The final stage of the delivery process, known as the 'last mile', represents the costly and environmentally damaging aspect of online retail. It is the stage that requires the greatest input of energy and carbon, making it the most energy- and carbon-intensive part of the entire process. (UNCTAD, 2024: 2). Last-mile delivery has the greatest impact on the environment and is the most inefficient stage of the supply chain (OliverWyman, 2021; Mangiaracina et al., 2015; Ranieri et al., 2018). Last-mile delivery is the final part of the supply chain operations, which aims to transport products from local depots to final customers. While being the final phase of a B2C parcel distribution service, last-mile delivery substantially elevated traffic congestion in urban areas (Ranieri et al., 2018; Viu-Roig and Alvarez-Palau, 2020).

Compared to traditional sales, however, the ratio of returns in e-commerce sales is generally higher, approximately 35% of original orders (Meyer, 1999). High return rates impose additional complexity on the transportation process. The collection of returned products becomes an important issue within the limited time of transportation. Late or delayed collection of returned products may also dissatisfy customers. Many internet-based direct sales companies (e.g., Hepsiburada, Trendyol) deliver orders of new products and collect returns simultaneously with their vehicles. Thus, the route of vehicles should be reconsidered concerning additional customers with returned products.

The supply chain for e-commerce logistics has the potential to pose significant environmental risks, potentially affecting biodiversity, food and water security, and local livelihoods (UNCTAD, 2024: 12-13). Freight transportation is a major contributor to CO_2 emissions, which adversely affect human health and contribute to environmental degradation. For instance, freight transportation is accountable for 21% of CO_2 emissions within the transport sector in the United Kingdom. (McKinnon, 2007: 4). E-commerce, however, has the potential to reduce environmental impact compared to conventional shopping by consolidating multiple customer trips into efficient home delivery routes (Matthews et al., 2001). The design of efficient vehicle routes has the potential to result in a reduction in the total fuel consumption of these vehicles, as well as in emissions to the environment.

The present study makes a contribution to the existing literature on the subject as follows. First, there is limited research on the environmental impacts of e-commerce logistics (Mangiaracina et al., 2015). Therefore, this study considers emission as a sustainability concern to determine the effects on the vehicle routing problem. Thus, the present study also adheres to Sustainable Development Goal 13, which deals with climate change (United Nations, 2024a). United Nations (UNStats, 2019) highlights that it is vital to reduce global carbon emissions to 45% by 2030 and achieve net zero emissions by 2050. Even though carbon dioxide emissions intensity declined, it is insufficient, thus, the United Nations calls for developing strategies for low-carbon energy, and energy-efficient solutions (United Nations, 2024b). There are also other calls for research to provide solutions for reducing carbon emissions (Şahinaslan et al., 2023; Samut, 2023). This will allow low-carbon transformations and help to achieve the goal of the Paris Agreement in the long term (United Nations, 2023). Therefore, businesses need to reduce their environmental impacts by handling logistics, and returns (UNCTAD, 2024). Incorporating sustainability into logistics also supports the achievement of sustainable development goals (Samut, 2023). Second, the current study considers the postponement of returned products from customers, however, too many uncollected items have the potential to cause customer dissatisfaction with the company in e-commerce logistics. Third, the clustering-based solution approach has been introduced to solve large-sized instances within reasonable solution times.

This study provides a mathematical model (i.e., a mixed integer programming - MILP) for a vehicle routing problem under returns and emission considerations in B2C e-commerce logistics. The suggested model considers emission as a sustainability concern to determine effects on the vehicle routing problem and allowance of returned products from customers where uncollected items have the potential to cause customer dissatisfaction toward the company in e-commerce logistics. The numerical analyses highlight the benefits that can be achieved through the proposed model and solution approach.

The remainder of this paper is structured as follows. Section 2 provides a brief literature review on e-commerce logistics, green vehicle routing problem, and last-mile delivery and the contribution of the current study in detail. Section 3 describes the considered problem and explains the structure of the mathematical model. Section 4 introduces the clustering-based solution approach to solve larger-sized problems within short computational times. Section 5 presents the numerical analyses to demonstrate the applicability of the aforementioned model. Finally, Section 6 concludes the study by discussing its limitations and potential directions for future research.

2. LITERATURE REVIEW

In general, a VRP, which was first introduced by Dantzig and Ramser (1959), aims to minimize total costs while determining the optimal route of vehicles in transportation. VRP is the most common problem considered by many researchers in the logistics industry. Currently, a considerable number of studies consider the variants of the vehicle routing problem (VRP). The classic VRP can be extended to various VRP variants such as time-dependent VRP (Çimen and Soysal, 2017), VRP with pickup and delivery (Soysal et al., 2020), inventory routing problem (Soysal et al., 2021), pollution routing problem (Bektaş and Laporte, 2011), sustainable VRP (Dündar et al., 2021) and green VRP (Erdoğan and Miller-Hooks, 2012).

Green VRP is an extension of the classic routing problem and is concerned with the minimization of energy consumption through the adoption of alternative-fueled and/or hybrid electric vehicles into the vehicle pool. Although early papers were published before 2010 (Barth et al., 2005; Apaydin and Gonullu, 2008; Silva et al., 2009), the mainstream of routing problems related to pollution emissions and energy consumption have gained significant attention from researchers since 2010 and have become a critical issue in recent years. Research on Green-VRP typically focuses on optimizing energy consumption to mitigate pollution in logistics and transportation activities. Transportation, fuel or energy consumption, and pollution are the three main dimensions of the green VRP. Conventional fossil fuel-powered vehicles, alternative-fueled, and hybrid electric vehicles are considered by papers in green VRP literature. Conventional fossil fuel-powered vehicles produce a considerable amount of greenhouse gases in the transportation of goods. The pollution routing problem seeks to minimize fuel consumption and CO_2 emissions generated by conventional fossil fuel-powered vehicles. Bektaş and Laporte (2011) introduce a more comprehensive objective function that not only accounts for the distance traveled by vehicles but also incorporates the costs of travel time, fuel, and greenhouse gas (GHG) emissions. On the other hand, alternative-fuel powered vehicles provide greener energy sources like hydrogen, natural gas, electricity, etc. (Erdogan and Miller-Hooks, 2012). Electric vehicles are a common example of alternative-fuel powered vehicles; however, their range in transportation is limited by the storage capacity of their batteries. Unlike electric vehicles, hybrid electric vehicles do not suffer from range limitations. Hybrid electric vehicles can overcome this obstacle by switching between fuel and battery power based on requirements that help lessen the need for frequent stops and reliance on infrastructure (Mancini, 2017). As a result, hybrid electric vehicles can help reduce the use of fossil fuels on other trips, leading to a decrease in both costs and CO_2 emissions. Green VRP extends the economic objectives of traditional VRP (e.g., travel cost, fuel/charging cost) with environmental objectives (e.g., fuel consumption, emissions), and social objectives (e.g., satisfaction, working hours of drivers).

Traditional logistics aims to transport products from one business to another business (B2B) under predetermined conditions. On the other hand, e-commerce logistics has become an important option for companies with the introduction of the internet and internet-based technologies in the B2C environment. In today’s business environment, e-commerce logistics is defined as the backbone of e-commerce operations (Delfmann et al., 2002).

The e-commerce supply chain generally consists of three main stages: first-mile, middle-mile, and last-mile. First-mile and middle-mile logistics operations are usually related to the transportation of products from the business to the business environment. Last-mile logistics, however, is mainly responsible for the transportation of products from local distribution centers to customers in a short time. Last-mile delivery poses significant challenges and costs in e-commerce logistics due to the stringent demands of consumer service (Vanelslander et al., 2013; Seghezzi and Mangiaracina, 2021). For detailed literature reviews on e-commerce logistics, readers can see the studies of Al Mashalah et al. (2022) and Risberg (2023).

The growing number of transactions in e-commerce forces companies to deploy more vehicles to meet customer needs on time during last-mile delivery. The addition of conventional fossil fuel-powered vehicles not only increases transportation costs but also has a negative impact on the environment by emitting greenhouse gases. As the final stage of e-commerce logistics, last-mile delivery should prioritize the reduction of carbon emissions along with transportation costs and customer satisfaction (Yu et al., 2024).

To highlight the related literature, we conducted a search for articles indexed in the Web of Science (WOS) database using the keywords "*e-commerce*", "*vehicle routing"* and "last-mile" within the "*topic*" field. Among the results, seventeen studies were manually selected based on their scope and empirical relevance. Table 1 exhibits a synopsis of the related literature.

The brief literature review reveals that some studies (Li et al., 2013 and Li et al., 2021 - location routing problem; Ge et al., 2018 and Zuhanda et al. 2023 – two-echelon VRP) consider e-commerce logistics in both strategic and tactical levels. The rest of the studies consider the tactical level of e-commerce logistics with variants of VRP (e.g., Moons et al., 2019 - Integrated order picking VRP; Fonseca-Galindo et al., 2022 – Dynamic VRP). Furthermore, only three studies (Li et al., 2013; Li et al. 2021; Zhang et al., 2021) considered the reverse flow of products. Li et al. (2013) suggest a mathematical model for LIRP where forward and reverse demands should be met at the same time. It is assumed that the returned products are without any defect in quality. The model aims to minimize the total cost of forward and reverse logistics. Li et al. (2021) consider a location-routing problem under the integration of collection and distribution. The suggested multi-objective model aims to minimize total logistics costs and maximize customer satisfaction, simultaneously. Zhang et al. (2021) extend a similar problem by considering the time window, and multi-depot assumptions. The model aims to minimize total transportation costs and penalty costs for late delivery.

Many studies consider fuel consumption and emission in the last-mile delivery of e-commerce in recent years. Tiwari and Sharma (2023) investigate the effect of emissions on routing decisions by considering emission cost with a side constraint. Total emission cost should not be over the pre-determined budget at the end of the distribution process. Yu et al. (2024) consider a multi-objective model that minimizes transportation costs and carbon emissions and maximizes customer satisfaction to solve the last-mile delivery problem. The results show that the proposed algorithm decreases transportation cost, and carbon emission amount and provides higher customer satisfaction.

Some studies suggest establishing pickup points instead of delivering parcels directly to customer locations (e.g., Wang et al., 2022) or consolidating deliveries to reduce the number of vehicles used (e.g., Muñoz-Villamizar, 2022), aiming to decrease fuel consumption and emissions. The studies that consider pickup points in last-mile delivery include Heshmati et al. (2019), Wang et al. (2022), and Wehbi et al. (2022). Heshmati et al. (2019) investigate various e-commerce delivery scenarios such as the impact of electric bicycles and cars, aggregated collection points, carrier bundling, and changing delivery times to minimize emission and routing costs. The results of the study show that delivering parcels to a collection point instead of home delivery provides a decrease in both transportation costs and the amount of emission. Wang et al. (2022) addressed a location-routing problem where the selection of pickup locations and delivery plans of green vehicles (i.e., electric vehicles) are optimized simultaneously. It has been noted that the branch & price algorithm suggested to solve the problem produces superior outcomes compared to commercial branch-and-cut solvers. Wehbi et al. (2022) present a study that introduces a model for a vehicle routing problem with portering (VRP-P) with time windows, which combines the use of on-foot porters and cargo vans in the delivery process. The model simultaneously determines both the vehicle routes and porter paths where a porter meets the vehicle at a handover point. The computational results of the study demonstrate that utilizing porters is advantageous, leading to up to a 50% reduction in journey times.

The studies that consider the consolidation of deliveries to reduce the number of vehicles used are Muñoz-Villamizar et al. (2022), Kahalimoghadam et al. (2024), and Xiao et al. (2024). Muñoz-Villamizar et al. (2022) approach tackles a multi-period strategy for pooling different shipments to evaluate their environmental impact. The pooling strategy of vehicles provides savings of 57% in total distance, 61% in total costs, and 56% in fuel consumption. Kahalimoghadam et al. (2024) address a collaborative multi-depot green vehicle routing problem to reduce CO_2 emissions by consolidated vehicle trips. The outcome of the study demonstrates that collaborative distribution provides a substantial reduction in travel distance (43.03%) and emission (25.93%), respectively. Xiao et al. (2024) focus on developing a green vehicle routing problem where cooperation between trucks and drones for rural last-mile delivery. According to the results, the cooperative delivery of parcels provides considerable energy savings of 31.34% in total.

Table 1. A brief overview of the literature on e-commerce logistics

Author(s)	*Problem*[*]	*Model*[**]	*Solution Method*[***]	*Objective*	*Sustainability Concern*	*Flow*[†]	*Postponement*
Li et al. (2013)	LIRP	ILP	HGSAA	Min	-	F, R	-
Ge et al. (2018)	2E-VRP	NLIP	TS	Min	-	F	-
Heshmati et al. (2019)	GVRP	MILP	Heuristics	Min	Energy consumption	F	-
Moons et al. (2019)	I-OP-VRP	MILP	RRT	Min	-	F	-
Liu (2020)	PDP	ILP	ACO	Max	-	F	-
Li et al. (2021)	LRP	MO-IP	LSNS-HAGA	Min, Max	-	F, R	-
Zhang et al. (2021)	MVRPSPDTW	MILP	DE	Min	-	F, R	-
Fonseca-Galindo et al. (2022)	DVRP	-	Heuristic	Min	-	F	-
Muñoz-Villamizar et al. (2022)	GVRP	MILP	-	Min	Emission	F	-
Tao et al. (2022)	MD-CVRP-OSA	IP	VNS	Min	-	F	-
Wang et al. (2022)	LRP-PS	MILP	B&P	Min	Energy consumption	F	-
Wehbi et al. (2022)	VRP-P	MILP	Clarke and Wright heuristic	Min	Emission	F	-
Tiwari and Sharma (2023)	GVRP	MILP	TS	Min	Emission	F	-
Zuhanda et al. (2023)	2E-MDCVRP	MILP	RNN	Min	-	F	-
Kahalimoghadam et al. (2024)	CMDGVRP	MOP	SAIWDSA	Min	Emission	F	-
Xiao et al. (2024)	GVRPD-SR	MILP	IALNS	Min	Energy consumption	F	-
Yu et al. (2024)	GRVP	MILP	DMPA	Min, Max	Emission	F	-
This study	GVRP	MILP	Exact – Clustering Algorithm	Min	Emission	F, R	✓

[*] 2E-MDCVRP: Multi-depot, capacity, two-echelon vehicle routing problem, 2E-VRP: Two echelon vehicle routing problem, CMDGVRP: Collaborative multi-depot green vehicle routing problem, DVRP: Dynamic vehicle routing problem, GVRP: Green vehicle routing problem, I-OP-VRP: Integrated order picking-vehicle routing problem, LRP: Location routing problem, LRP-PS: Location-routing problem with pick-up stations, LIRP: Location-inventory-routing problem, MD-CVRP-OSA: Multi-depot capacitated vehicle routing problem with order split and allocation, MOP: Multi-objective programming, MVRPSPDTW: Vehicle routing problem with simultaneous pickup and delivery with time windows from multiple depots, PDP: Pickup and delivery problem, VRP-P: Vehicle routing problem with portering

[**] ILP: Integer linear programming, IP: Integer programming, LSNS-HAGA: Large-Scale neighborhood search strategy and hybrid adaptive genetic algorithm, MILP: Mix integer linear programming, MO-IP: Multi-objective integer programming, NILP: Non-linear integer programming.

[***] ACO: Ant colony optimization, B&P: Branch-and-price algorithm DE: Differential evolutionary algorithm, DMPA: Discrete marine predators algorithm, HGSAA: Hybrid genetic simulated annealing, IALNS: Improved adaptive large neighborhood search, RNN: Repetitive nearest neighbor algorithm, RRT: Record-to-record travel algorithm, SAIWDSA: Self-adaptive intelligent water drops simulated annealing, TS: Tabu search algorithm, VNS: Variable neighborhood search.

[†] F: Forward, R: Reverse

The review of the literature reveals that, to the best of our knowledge, no study has considered allowance in the collection stage of returned products. Therefore, this study represents a contribution to the existing literature on the subject by considering: *i)* emission to determine effects on the vehicle routing problem, *ii)* the postponement of the collection of returned items due to the limited delivery time, *iii)* proposing the cluster-based solution approach to tackle with larger-sized problems.

3. METHODOLOGY

3.1. Problem Description

The current section exhibits a formal description of the considered problem. Here, $N = \left\{D, R_{cur}, R_{pr}, \{0\}\right\}$ is the set of all nodes, where $D = \{1,2,\dots,m\}$ is a set of customers, $R_{cur} = \{1,2,\dots,n\}$ is a set of return points of the current period, $R_{pr} = \{1,2,\dots,p\}$ is a set of return points of the previous period and $\{0\}$ refers to the depot that serves as both the initial and final point of departure for vehicles. The vehicle set is represented by $K = \{1,2,\dots,k\}$.

A company is primarily responsible for forward distribution to meet customer demands. Furthermore, vehicles may collect returned items from customers due to several reasons (e.g., misdelivery, right of withdrawal, etc.) while distributing process of new items. However, the vehicle fleet may not collect all returned items because of the limited time available for the distribution process. Unsatisfied demands for the collection of returned items should be met in the next period and a penalty cost (c_p) is incurred to alleviate the negative effect of the late collection process.

The fleet consists of conventional type vehicles which produce a considerable amount of greenhouse gases to the environment. Each vehicle *k* consumes the amount of fuel in liters. To calculate the fuel consumption of each vehicle *k*, we follow Barth et al. (2005) approach. Several studies (e.g. Demir et al., 2014; Soysal et al. 2021) use this approach for fuel estimation. The energy consumption of a vehicle for traveling a distance *d* (m) at a constant speed *v* (m/s) is calculated with the help of the following formulations:

$$FC = \lambda(\eta\ (d\ /\ v) + \gamma\beta v^2 + \gamma\theta(\mu + F)d) \tag{1}$$

where FC refers to the fuel consumption, $\lambda = \xi/\kappa\psi$, $\eta = k_e N_e V_e$, $\gamma = 1/(1000\varepsilon\varpi$, $\beta = 0.5 C_d A_e \rho$, and $\theta = \mathrm{g}\sin\phi + g\ C_r \cos\phi$ (Note that we employ the notations from Barth et al., 2005 approach).

Each vehicle begins and ends its delivery operations at the depot with a fixed cost c_{fix} of operating the vehicle. Let c_{fuel} refers to the energy cost. The considered problem is to determine optimal vehicle routes by minimizing the total cost, including transport, penalty, and fixed costs.

3.2. Mathematical Model

The current section describes a MILP formulation of the addressed problem. The formulation starts with the objective function. Table 2 presents the notations considered in the model.

Table 2. Notations

Sets	*Description*
N	The set of all nodes
D	The set of forward demand
R_{cur}	The set of returned items demand in the current period
R_{pr}	The set of returned items demand in the previous period
K	The set of vehicles
Parameters	
$d_{i,j}$	the distance between nodes *i* and *j*, $i,j \in V$
$v_{i,j}$	the speed between nodes *i* and *j*, $i,j \in V$
$t_{i,j}$	the travel time between nodes *i* and *j*, $i,j \in V$
α_i	Service time at the node *i*
c_{fuel}	The fuel cost of a vehicle
c_p	A penalty cost for a delay
c_{fix}	Fixed cost of operating a vehicle
T	The latest time of the delivery
M	A sufficiently large number
λ, γ, β, η, θ, μ	Technical parameters
Variables	
$X_{i,j,k}$	1 if vehicle *k* travels from *i* to *j*, otherwise 0, $i,j \in V$
Y_i	Auxiliary variables

Minimize

$$\sum_i^N \sum_{j;i\neq j}^{N\backslash 0} \sum_k^V \lambda\left(\eta\ \left({}^{d_{ij}}/_{v_{ij}}\right) + \gamma\beta v^2 X_{i,j,k} + \gamma\theta\left(\mu X_{i,j,k}\right)d_{ij}\right) c_{fuel} + \sum_j^{R_{cur}} c_p\left(1 - \sum_{i;i\neq j}^N \sum_k^V X_{i,j,k}\right) + \sum_j^{N\backslash 0} \sum_k^V X_{0,j,k} \tag{2}$$

The objective function (Equation 2) comprises the cost of energy consumed due to delivery operations, penalty cost for unmet demand of returned items, and fixed cost for operating a vehicle.

Subject to:

$$\sum_j^{N\backslash 0} X_{0,j,k} = 1, \quad \forall\ k \in V \tag{3}$$

$$\sum_{i}^{N\backslash 0} X_{i,0,k} = 1, \quad \forall\, k \in V \tag{4}$$

$$\sum_{i:i\neq j}^{N} X_{i,j,k} = \sum_{i:i\neq j}^{N} X_{j,i,k}, \quad \forall\, j \in N\backslash 0,\ k \in V \tag{5}$$

$$\sum_{i:i\neq j}^{N} \sum_{k}^{V} X_{i,j,k} = 1, \quad \forall\, j \in D \tag{6}$$

$$\sum_{i:i\neq j}^{N} \sum_{k}^{V} X_{i,j,k} = 1, \quad \forall\, j \in R_{pr} \tag{7}$$

$$\sum_{i:i\neq j}^{N} \sum_{k}^{V} X_{i,j,k} \leq 1, \quad \forall\, j \in R_{cur} \tag{8}$$

$$\sum_{j:i\neq j}^{N} X_{i,j,k} \leq 1, \quad \forall\, i \in N, k \in V \tag{9}$$

$$0 \leq \sum_{i}^{N} \sum_{j:i\neq j}^{N\backslash 0} \sum_{k}^{V} t_{ij} X_{i,j,k} \leq T \tag{10}$$

$$Y_i + \sum_{k}^{V} t_{i0}\, X_{i,0,k} \leq T, \forall\, i \in N\backslash 0 \tag{11}$$

$$Y_j - Y_i - t_{ij} - \alpha_i \geq M\left(1 - \sum_{k}^{V} X_{i,j,k}\right), \forall\, i \in N, j\ \in N\backslash 0 \tag{12}$$

$$X_{i,j,k} \in \{0,1\}, \forall\, i,j \in N, k \in V \tag{13}$$

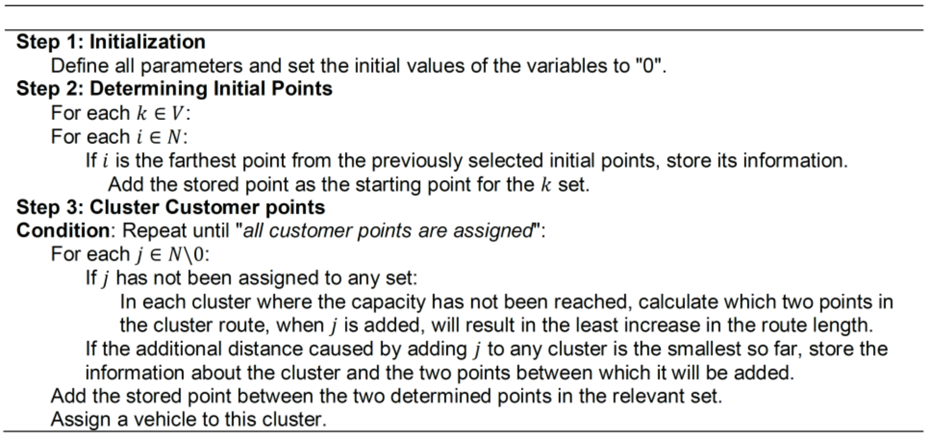
$$Y_i \geq 0, \forall\, i \in N \tag{14}$$

Equations 3 and 4 guarantee that a vehicle should start and end its routes at the depot {0}. Equation 5 guarantees a balance between the inflows and outflows at each of the nodes. Equations 6 and 7 guarantee that demands of forward flow points and returned items of the previous period should be met within the current period. Equation 8 allows that demand for returned items may or may not be met in the current period. Equation 9 ensures that only one vehicle can traverse from a node at the same time. Equations 10 and 11 force that the trip of a vehicle cannot exceed the latest time of the working hours. Equation 12 ensures that a vehicle can complete the tour without the possibility of undertaking any sub-tours. Equations 13 and 14 impose limitations on the decision variables.

4. CLUSTERING-BASED SOLUTION APPROACH

The clustering approach in routing problems typically involves partitioning the points to be visited into clusters based on specific characteristics, and then determining routes for each cluster individually before combining them (Erdogan and Miller-Hooks, 2012; Sutrisno and Yang, 2023). This partitioning reduces the problem size and helps shorten computation time. The suggested solution approach, which focuses on solving large-sized problem instances by breaking them down into smaller components, can be summarized in Algorithm 1.

The clustering process begins with the selection of an initial point for each cluster. To ensure that the clusters are relatively distinct from one another, it is recommended to choose the points that are farthest apart as the initial points for the clusters. Following the selection of the initial points, traveling salesman routes are created starting from these points to form the clusters. In each iteration, each potential point is analyzed for each cluster to determine which two nodes in the current route the point should be inserted between, to minimize the total distance increase. In the clustering phase of customer points, it is recommended to impose a capacity constraint on the clusters. This constraint ensures the formation of relatively balanced clusters, allowing the model to be applied effectively. If a large problem is divided into sub-problems, some sub-problems may become very small, while others remain disproportionately large. This imbalance would negate the advantages of the clustering approach.



```
Step 1: Initialization
    Define all parameters and set the initial values of the variables to "0".
Step 2: Determining Initial Points
    For each $k \in V$:
    For each $i \in N$:
        If $i$ is the farthest point from the previously selected initial points, store its information.
            Add the stored point as the starting point for the $k$ set.
Step 3: Cluster Customer points
Condition: Repeat until "all customer points are assigned":
    For each $j \in N\backslash 0$:
        If $j$ has not been assigned to any set:
            In each cluster where the capacity has not been reached, calculate which two points in
            the cluster route, when $j$ is added, will result in the least increase in the route length.
        If the additional distance caused by adding $j$ to any cluster is the smallest so far, store the
        information about the cluster and the two points between which it will be added.
    Add the stored point between the two determined points in the relevant set.
    Assign a vehicle to this cluster.
```

Figure 1. Clustering-based solution approach

5. FINDINGS

The present section describes a numerical analysis to demonstrate the suitability of the model for addressing the aforementioned problem. We obtained the results by using the CPLEX 12.6 optimization package on a computer with a Pentium(R) i5 2.40GHz CPU and 16GB memory.

First, we outline the problems and the data utilized for analysis. Next, we evaluate optimal solutions across various scenarios. We provide Key Performance Indicators (KPIs): *(i)* total cost, *(ii)* total fuel amount, *(iii)* total postponement number, *(iv)* total traveled distance, *(v)* total traveled time, and (vi) total emission amount.

5.1. Base Case

We use the data from the Pollution Routing Problem Instance Library (2024). Then, we have adapted the distances of the UK50_01 instance by considering one-fourth of the original distances to imitate an urban environment. The logistics network involves a depot and 25 customers for forward and 25 customers for reverse flow points.

For the base case, the vehicle fleet consists of two homogeneous vehicles with a 2000 TL fixed cost. The fuel cost is approximately 45 TL per liter. The penalty cost for unsatisfied demands for the collection of returned items is 500 TL per customer. Vehicles should complete both forward and reverse transportation within 8 hours. Table 3 presents base case results considering the defined KPIs.

Table 3. Base case results

KPIs	*Value*
Total cost (TL)	11390
Total fuel amount (liter)	43.22
Total postponement number (customer)	7
Total traveled distance (km)	446.95
Total traveled time (hour)	7.75
Total emission amount (kg)	227.41

According to the result, vehicles were not able to visit 7 customers with demand for return items within working hours. Thus, the company should pay 3500 TL to unsatisfied customers to alleviate the negative effects of postponed delivery. To complete the delivery, vehicles consume approximately 43 liters by releasing 227 kg of CO_2 into the air.

5.2. The Effect of Return Postponement

The proposed model respects the postponement of returned items due to the limited delivery time. This subsection aims to show the effect of return postponement on KPIs through an additional analysis. We assume that both forward and reverse demands should be met on the same day, so reverse demand cannot be postponed. This means that equation 10 can be violated by the extended total travel time of vehicles. Equation 8 has been replaced with Equation 15.

$$\sum_{i:i\neq j}^{N} \sum_{k}^{V} X_{i,j,k} = 1, \quad \forall\, j \in R_{cur} \tag{15}$$

Table 4. Summary results for respecting the postponement of returned items

KPIs	*Value*
Total cost (TL)	8967
Total fuel amount (liter)	55.18
Total postponement number (customer)	0
Total traveled distance (km)	570.61
Total traveled time (hour)	9.9
Total emission amount (kg)	290.33

The results of both total fuel consumption and total emission amount have been increased by approximately 27% (Table 4), due to longer vehicle trips than the base case. Although total cost decreased because of no reverse demand postponement, vehicles did not visit all customers within the pre-determined delivery time. This solution becomes unfeasible for the considered problem. It seems more realistic to consider the postponement of reverse demand rather than forward demand for decision-makers in real-life applications. Since in real life, the distribution process has to be carried out within limited times of the day, decision-makers have to take the risk of postponing some returns.

5.3. The Effect of the Return Collection

This subsection demonstrates the effect of return collection on KPIs, we assume that forward and reverse demands have been collected by different vehicles. Thus, routes of forward and reverse demands have been separated from each other. We replaced Equations 6-8 with Equations 16-18.

$$\sum_{i:i\neq j}^{N} X_{i,j,1} = 1, \quad \forall\, j \in D \tag{16}$$

$$\sum_{i:i\neq j}^{N} X_{i,j,2} = 1, \quad \forall\, j \in R_{pr} \tag{17}$$

$$\sum_{i:i\neq j}^{N} X_{i,j,2} \leq 1, \quad \forall\, j \in R_{cur} \tag{18}$$

Table 5. Summary results for the effect of return collection on KPIs

KPIs	*Value*
Total cost (TL)	11087
Total fuel amount (liter)	78.75
Total postponement number (customer)	0
Total traveled distance (km)	814.14
Total traveled time (hour)*	7.42
Total traveled time (hour)**	6.70
Total emission amount (kg)	414.23

* Vehicle responsible for forward distribution
** Vehicle responsible for reverse collection

Table 5 presents the KPIs of the network where routes of forward and reverse demands are separately delivered by different vehicles. The results demonstrate that both the total fuel amount and total emission amount have considerably increased (i.e., approximately 82%) for the base case. The main reason is the inefficient routing of vehicles although the total postponement number is none. These results imply that separating distribution and collection operations is not an efficient decision for a company concerning total fuel consumption and total emissions released into the air because of the long routes of vehicles.

5.4. The Effect of Considering Emission

In the proposed model, total transportation energy consumption or emissions serve as indicators to evaluate the performance of logistics operations in terms of environmental externalities. The model quantifies the overall environmental impact in terms of cost, incorporating fuel and electricity consumption components within the objective function. In this subsection, the objective function is adjusted to enable the model to deliver an optimal solution that minimizes the total environmental impact. In specific, penalty cost for unmet demand of returned items and fixed cost for operating a vehicle are removed from the objective function. The new formulation is optimized with an environmental objective function that focuses solely on the emission levels generated by fossil fuel-powered vehicles. Table 7 presents where the objective function is the same as the base case and the objective is the minimization of emissions, respectively.

Table 7. Resulting vehicle routes from the distribution networks where the objective function is the same as the base case and the objective is the minimization of emissions, respectively

Vehicle	*Route*
Base Case	
1	Depot-1-2-4-6-7-8-13-14-15-16-17-21-25-26-37-38-41-44-45-46-47-48-50-Depot
2	Depot-3-5-9-10-11-12-18-19-20-22-23-24-27-29-30-33-34-42-43-49-Depot
The adjusted model for minimizing emission	
1	Depot-1-2-4-6-7-8-13-14-15-16-17-21-25-45-49-Depot
2	Depot-3-5-9-10-11-12-18-19-20-22-23-24-46-47-48-50-Depot

The results indicate that the solution from the adjusted model achieves a reduction of nearly 17% in total emission amount. However, adopting environmentally friendly measures leads to postponing all customers who expect the collection of returns in the current period. The postponement of returns may cause a significant number of unsatisfied customers. Furthermore, the adjusted model generates different vehicle routes compared to those observed in the base cases. The analyses presented in this subsection show that environmentally friendly delivery plans may not be economically viable for transportation companies in last-mile logistics. To mitigate the negative environmental externalities of transportation operations, vehicle routes, and fleet composition may need to be adjusted.

5.5. Numerical Analyses on Larger-Sized Problems

In this subsection, we investigate the performance of the clustering-based solution approach in relatively larger instances. The data for the large-sized problems are also taken from “The Pollution-Routing Problem Instance Library". We have used 5 instances from each problem set with 150 customers (UK150_01 to `UK150_05), and 200 customers (UK200_01 to `UK200_05). In line with the base case, the distances of instances that include 150 and 200 customers by considering one-six and one-eighth of the original distances to emulate urban logistics network for last-mile delivery.

Table 8. **Comparison of the performance exact solutions and the clustering-based solution algorithm in large-sized instances**

		Total cost (TL)			*Solution Time (hours)*		
No	*Instance*	*Exact solution*	*The Proposed Approach*	*% diff.*	*Exact Solution*	*The Proposed Approach*	*% diff.*
1	UK150_01	26497	27428	3.51	6.68	0.84	-87.37
2	UK150_02	30500	32290	5.87	6.36	0.90	-85.83
3	UK150_03	21973	23150	5.36	6.45	0.71	-88.96
4	UK150_04	23965	26054	8.72	6.87	0.73	-89.34
5	UK150_05	21000	22063	5.06	6.39	0.53	-91.71
6	UK200_01	20004	21252	6.24	12.76	1.71	-86.58
7	UK200_02	20485	22704	10.83	12.68	1.94	-84.68
8	UK200_03	20996	21995	4.75	12.92	1.98	-84.70
9	UK200_04	20551	21516	4.69	12.98	1.88	-85.48
10	UK200_05	24500	25489	4.04	12.95	1.57	-87.87

The results show that the clustering-based solution approach provides promising solutions concerning total cost. Except for Instance 7 (UK200_02), the total cost difference between the exact solution and the solutions obtained from the proposed algorithm does not exceed 10%. This shows that the algorithm is an effective tool for managers to employ feasible delivery plans in last-mile delivery operations. Furthermore, the clustering-based solution approach outperforms the MILP model in terms of solution time, with the algorithm being, on average, 87% faster than the MILP model. Therefore, the proposed solution approach can be considered a robust alternative for decision-makers when handling practically-sized routing instances.

6. CONCLUSION

The extensive adoption of the Internet and technological advancements provide a significant contribution to the growth of the e-commerce industry, supplanting traditional trade methods. Especially in extraordinary outbreaks such as the COVID-19 era, e-commerce has been considered a more important and preferred method for consumers. Customers' demand for fast and reliable delivery from the e-commerce industry requires timely and error-free distribution of products to customers. Last-mile logistics, which primarily involves transporting products from local distribution centers to customers within a short time frame, is the crucial stage in the e-commerce supply chain. Every improvement in logistics leads to time and cost savings for logistics companies and the entire economy through the supply chain (Şahinaslan et al., 2023).

This study addresses a vehicle routing problem under returns and emission consideration in B2C e-commerce logistics. The proposed MILP model is unique for the considered problem in respecting comprehensive emissions function and simultaneous delivery of both forward and reverse demands. We presented the added value of the MILP model with a base case and two additional analyses. The numerical analysis for the base case shows that the suggested model can assist decision-makers in coordinating forward distribution and reverse collection decisions within the context of sustainable e-commerce logistics. The results of additional analyses have indicated that it would be beneficial to consider the possibility of simultaneous return collection and the postponement of returns. The result of the adjusted model for minimizing emission shows that a reduction of nearly 17% in total emission amount can be achieved, however, the adjusted model postpones all demand for the collection of returned items. Furthermore, the cluster-based solution approach causes a considerable decrease in solution time while providing promising solutions. Disregarding these aspects may lead companies to endure increased fuel and emissions in the e-commerce industry. The current study reduces emissions by improving routes. Future research can consider electric vehicles, hydrogen-fuel-cell vehicles, or even drones (McKinsey & Company, 2021: 3).

It is important to acknowledge the limitations of the research to inform future attempts. Firstly, it should be noted that this study does not take into account the potential uncertainty regarding forward and reverse demands. Secondly, the vehicle capacity and weights of the products in question are disregarded, despite the potential for such factors to influence the optimal routing of a vehicle. In this study, only static demand has been taken into consideration, however, demands can be changed dynamically due to various reasons.

A future attempt could be to address pickup points instead of delivering and collecting parcels directly to and from customer locations in both forward and reverse flows. Another possible extension of the paper is to consolidate deliveries to reduce the number of vehicles used. These dimensions offer opportunities for future studies on the topic.

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No potential conflict of interest was declared by the author.

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Compliance with Ethical Standards

It was declared by the author that the tools and methods used in the study do not require the permission of the Ethics Committee.

Ethical Statement

It was declared by the author that scientific and ethical principles have been followed in this study and all the sources used have been properly cited.

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